4^{th} Generation Light Source Injector Requirements

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- The definition of electron injector

- The role of electron sources and injectors in light sources.

- Requirements for electron sources and injectors in 4th generation light sources.

What is an Electron Injector?

The electron injector is the initial part of an accelerator (chain) where the electrons are generated and conditioned (at some level) to match the requirements of the following main accelerator.

The injector obviously initiates with an electron source, but where does it end?

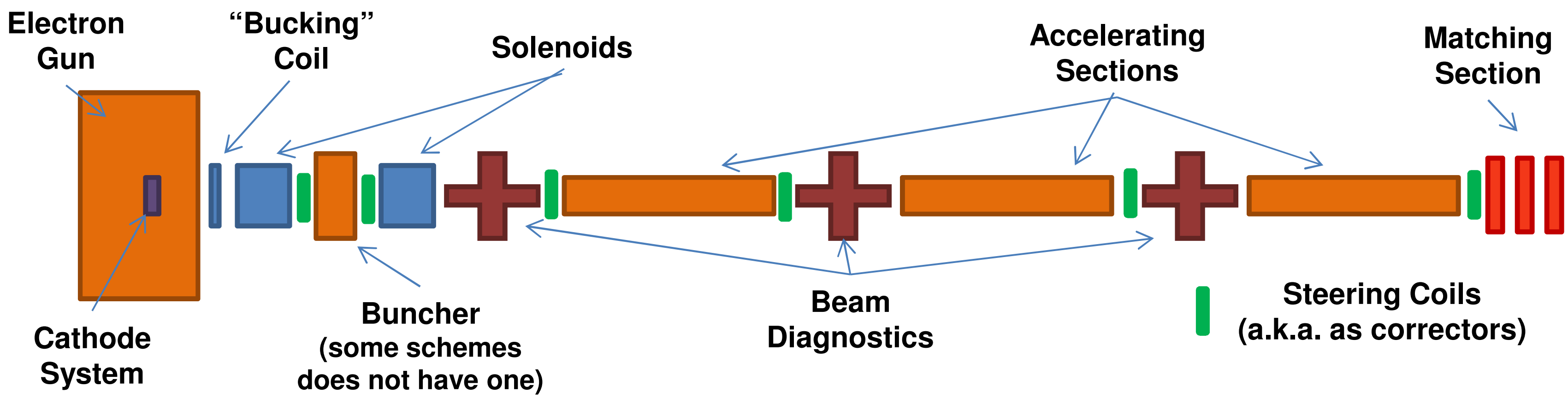
Space charge forces play a central and in most of the cases a dominant role in limiting and spoiling the quality of an electron beam.

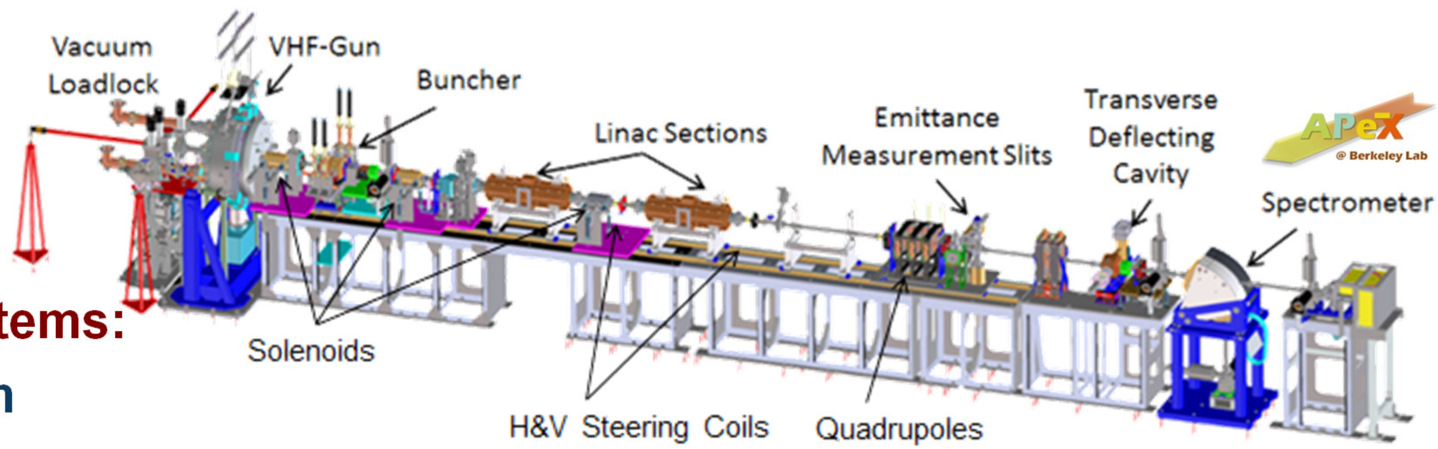
Space charge forces scale inversely with the square of the beam energy.

In the typical assumption, the injector should accelerate the electron beam up to energies sufficient to make space charge forces very small or preferably negligible.

It will be also clear later in the course that the ultimate beam quality in a linac based accelerator is defined at the injector.

The Typical High-Brightness Injector Layout





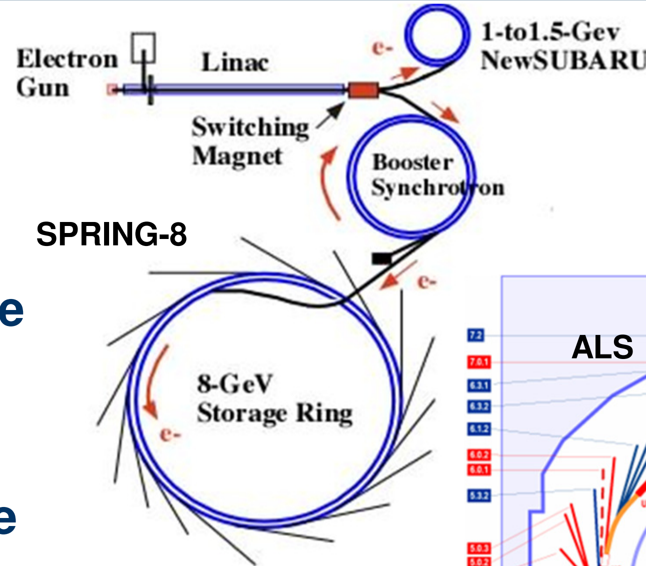
Injector Sub-Systems:

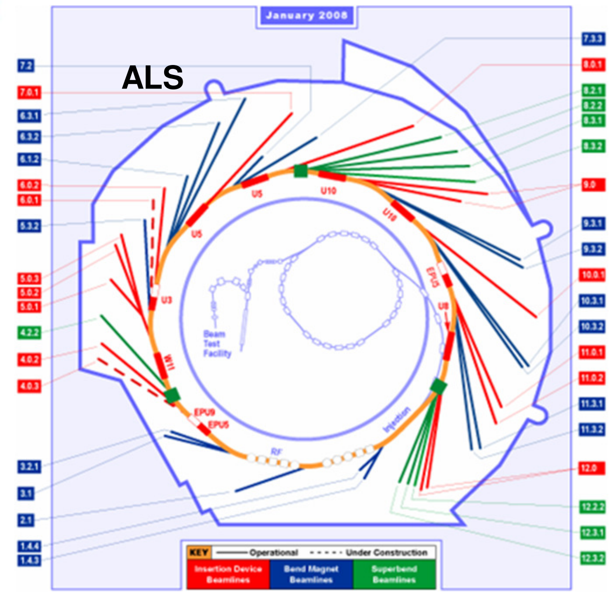
- Cathode system
- Electron gun
- Focusing and steering system
- Compression system
- Emittance compensation system
- Accelerating system
- Diagnostics system

Much more details in the next lectures!

The Role of the Electron Injector in Light Sources

- *1st generation*: "parasitic" synchrotron radiation sources from dipoles in colliders.
- *2nd generation*: dedicated storage rings with light ports in dipoles
- *3rd generation*: dedicated storage rings with *insertion devices* (undulators, wigglers)
- *4th generation*: free electron lasers, energy recovery linacs…

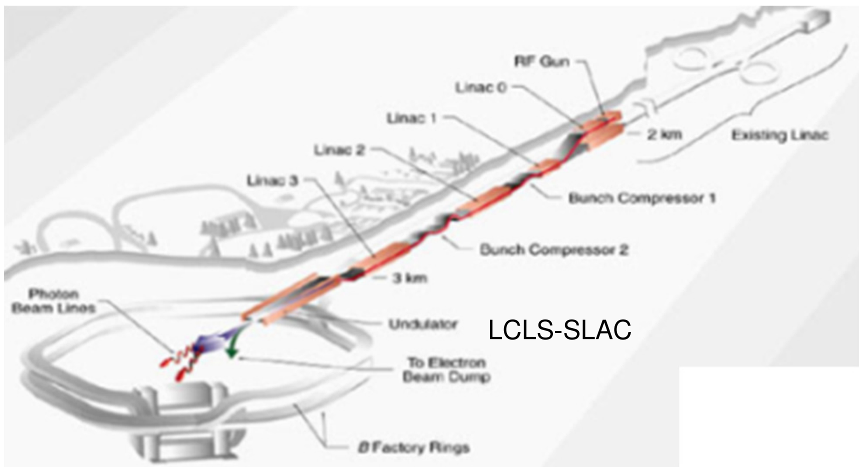




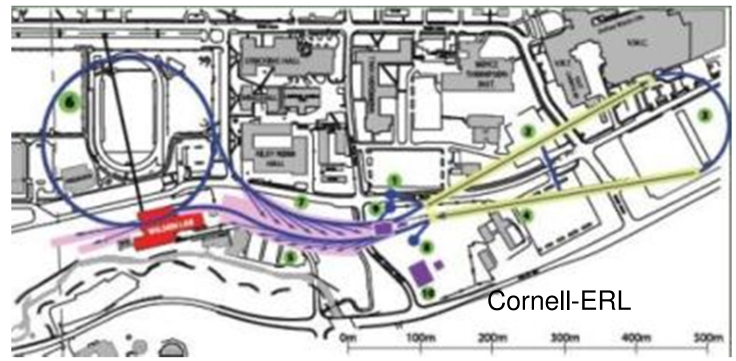
In 1st, 2nd and 3rd gen. light sources, electron sources are part of the injector chain that typically includes a small linac and a "booster/accumulator" ring. The beam generated by the electron gun goes through the linac and is then accelerated and stored in the booster for a time long enough that the 6D beam phase-space distribution is fully defined by the equilibrium characteristics of the booster and not of the electron source.

4th GENERATION LIGHT SOURCES

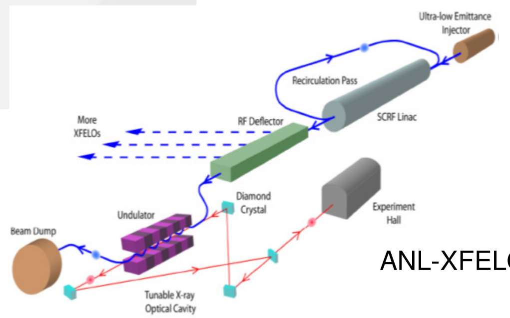
In linac based 4th generation light sources, such as free electron lasers (FELs) and energy recovery linacs (ERLs), the electron beam goes through the accelerator only once or few times.



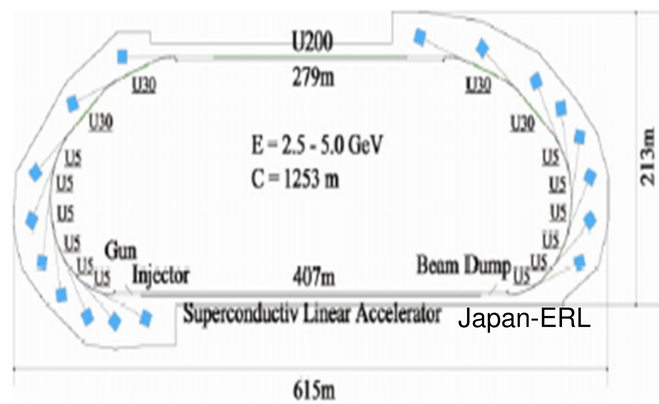
LCLS-SLAC



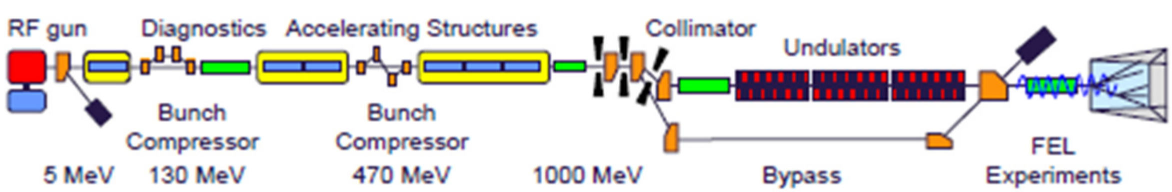
Cornell-ERL



ANL-XFELO



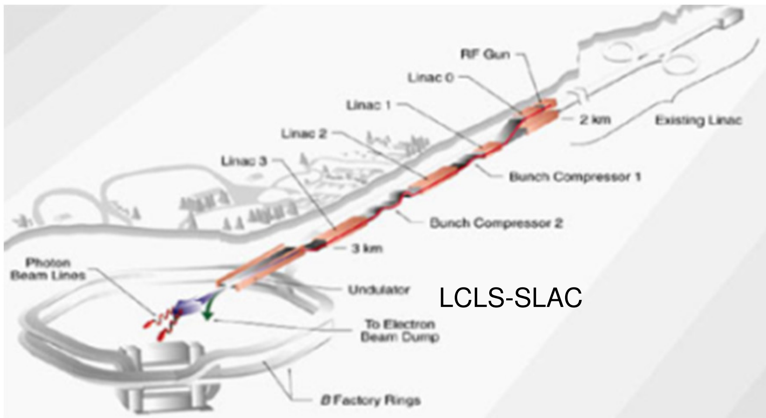
Japan-ERL

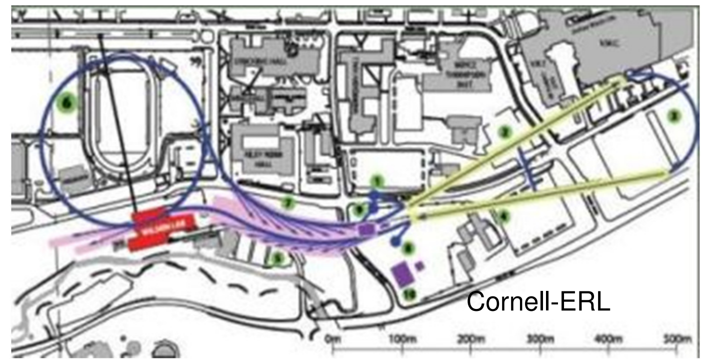


FLASH-DESY

The Role of the Electron Injector in 4th Generation Light Sources

With just a few beam passages in the accelerator, the final beam quality is set in the linac and ultimately by its injector and electron source.





In such facilities, the requirements for a large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, translate into high particle density 6D phase-space, or in other words, in high brightness B:

$$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}} \quad ?$$

with N_e the number of electrons per bunch and $\varepsilon_{nx,\,ny,\,nz}$ the normalized emittances for the planes x, y, and z

The brightness generated at the electron source represents the ultimate value for such a quantity, and cannot be improved but at best preserved along the downstream accelerator

X-Ray 4th Generation Light Sources, the Most Challenging Electron Injector Case

• In FELs, the matching condition for transverse emittance drives towards small normalized emittances.

$$\varepsilon \approx \frac{\lambda}{4\pi} \Rightarrow \frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

• The minimum obtainable value for ε_n defines the energy of the beam ($\gamma = E/mc^2$).

(with β the electron velocity in speed of light units, and assuming that an undulator with the proper period λ_u and undulator parameter K can be built: $\lambda = \lambda_u / 2\gamma^2(1 + K^2/2)$)

• We will see later, that for the present electron gun technologies: $\varepsilon_n <$ ~1 μm for the typical < ~1 nC charge/bunch.

For X-Ray machines ($\lambda <$ ~1 nm) that implies GeV-class electron beam energy, presently obtainable by long and expensive linacs.

• Similar transverse emittance requirements apply also to ERLs.

• In X-Ray FELs the matching condition for the energy spread requires a fairly low energy spread as well

$$\frac{\sigma_E}{E} < \sim \rho_{Pierce} < \sim 10^{-3}$$

• Achieving the necessary FEL gain requires high peak current (~ 1 kA), and hence high charge/bunch and short bunches.

• High time-resolution user-experiments require extremely short X-Ray pulses (down to sub-fs) imposing the need for small and linear longitudinal emittances to allow for the proper compression along the linac.

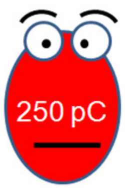
In summary, 4th generation X-Ray facilities challenge the performance of electron injectors. These lectures from now on will focus on such a type of injectors

Requirements for the electron injector

Charge per Bunch

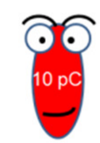
In order to exploit all the different modes of operation of ERLs and FELs, the injector must operate within a very broad range of charge/bunch.

- **For example, experiments in FELs requiring large number of photons per pulse or very narrow transform limited photon bandwidth in seeded FEL schemes require longer bunches and hence higher charges per bunch that can approach the nC.**



- **The main operational mode for X-Ray FELs relies on a charge/bunch of a few 100s pC (~ 100 pC for ERLs), where a satisfactory tradeoff between the number of photons/pulse and a moderate transverse emittance increase at the injector due to space charge forces can be found.**

- **Smaller charges per bunch (from few tens of pC down to the pC) are being used as alternate/complementary modes of operation. Because of the lower charge/bunch, space charge effects can be more efficiently controlled making electron guns capable of generating beams with smaller transverse and longitudinal normalized emittances. The resulting higher 6D brightness allows for shorter FEL gain lengths at a relatively moderate electron beam energy.**



In ERLs the low emittance potentially obtainable with few tens of pC charge/bunch allows for modes of operation with X-Ray pulse with full transverse coherence.

Emittance

It was previously mentioned that the major objective for electron injectors is to maximize brightness

$$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

For a fixed charge/ bunch that translates in minimizing the emittance in each of the planes.

The **normalized emittance** in each plane is proportional to the area in the phase space occupied by the beam.

$$\varepsilon_{nw} = \sigma_w \frac{\sigma_{pw}}{mc} \qquad w = x, y, z$$

σ *indicates r.m.s. quantities*

In **Hamiltonian** systems the normalized emittance is an invariant of motion (Liouville's theorem).

For a constant energy beam, the **geometric emittance** is an invariant of motion and is defined (in the transverse plane) as:

$$\varepsilon_w = \frac{\varepsilon_{nw}}{\beta\gamma} = \sigma_w \frac{\sigma_{pw}}{\beta\gamma\, mc} = \sigma_w \frac{\sigma_{pw}}{p} = \sigma_w \sigma_{w'} \quad with \quad w = x, y \;\; and \quad w' = \frac{p_w}{p}$$

For a given set of particles (beam) the r.m.s. **geometric emittance** is defined as

$$\varepsilon_{w\,rms} = \sqrt{\langle w^2\rangle\langle w'^2\rangle - \langle ww'\rangle^2} \qquad w = x, y$$

The r.m.s. emittance is not conserved in the presence of nonlinear forces

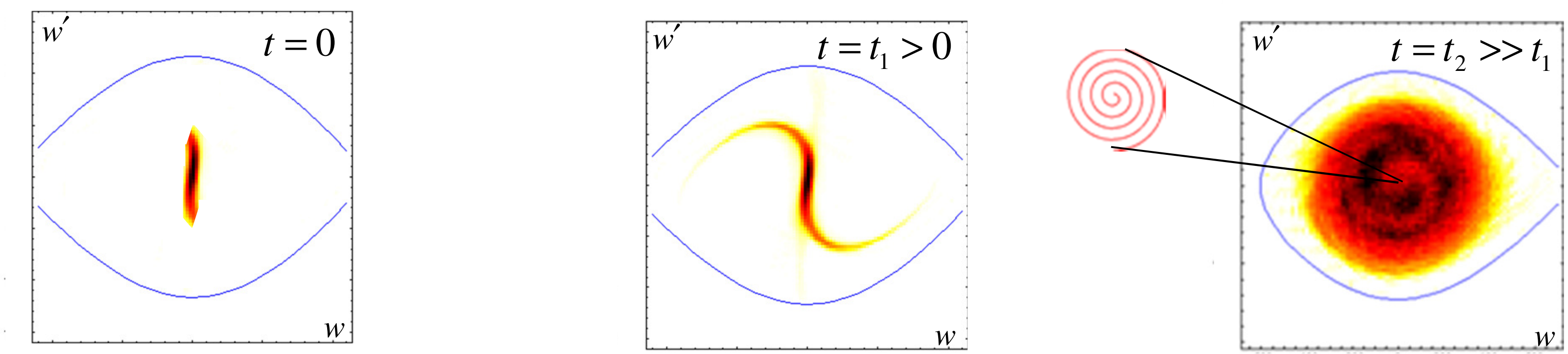
Emittance Filamentation

• We already mentioned that in the case of Hamiltonian systems, as a consequence of the Liouville Theorem the emittance is conserved.

• This is true even when the forces acting on the system are **nonlinear** (space charge, nonlinear magnetic and/or electric fields, …)

• This is **not** true in the case of the rms emittance.
In the presence of nonlinear forces the rms emittance is not conserved.

• Example: *filamentation*. In the presence of nonlinear forces, particles with different phase space coordinates move with different velocity along the phase space trajectories.



• The emittance according to Liouville is still conserved.

But the rms emittance calculated at later times **increases.**

Transverse Emittance

• Small normalized transverse emittances are extremely important in X-Ray FELs because the required matching between the small X-Ray photon emittance and the electron beam geometric emittance

$$\varepsilon \approx \frac{\lambda}{4\pi} \quad \Rightarrow \quad \frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

can be achieved at lower beam energies (assuming that undulators with the required period are feasible).

• Also, small emittances in SASE FELs allow for shorter gain lengths and thus for shorter undulators.

$$P(z) = P_0 e^{z/L_G}$$

$$\rho_{Pierce}^{1D} = \frac{1}{\gamma}\left[\frac{1}{64\pi^2}\frac{I_e}{I_A}\frac{1}{\varepsilon_x \beta_x}\lambda_u^2 K^2 JJ^2\right]^{1/3}; \qquad L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho_{Pierce}^{1D}} \quad gain\ \ length$$

(3D effects add further dependence of the gain length on the geometric emittance)

• In ERLs high electron brightness translates directly into high photon brightness.

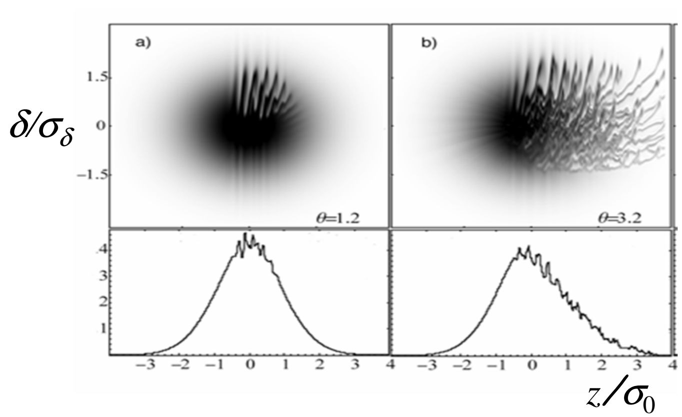
• This makes small emittances particularly important allowing to effectively reduce the size and the cost of expensive X-Ray FEL and ERL facilities.

• The minimum achievable ε_n depends on the charge/bunch.
At lower charges, it is possible to reduce the beam size at the cathode while still keeping under control space charge.
We will see later that smaller sizes at the cathode imply smaller emittances.

Longitudinal Emittance

• When discussing longitudinal emittance requirements for injectors, two different cases need to be considered.

• In the relatively high charge/bunch regime (few hundreds of pC and above), the rising of the microbunching instability (MBI) in linac magnetic compressors, forces to use 'heating' techniques (e.g. laser heating) to increase the uncorrelated energy spread and damp the instability. In this situation, the injector longitudinal emittance is generally not relevant.



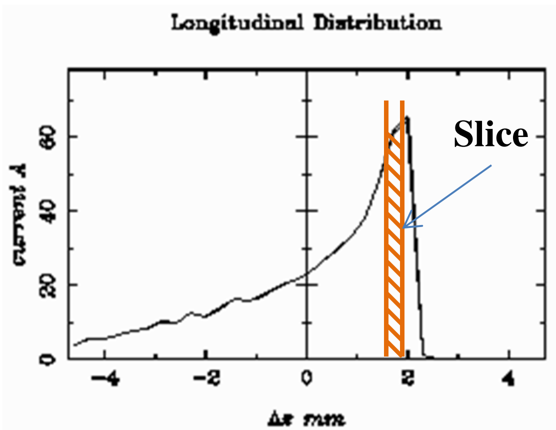
Courtesy of Marco Venturini

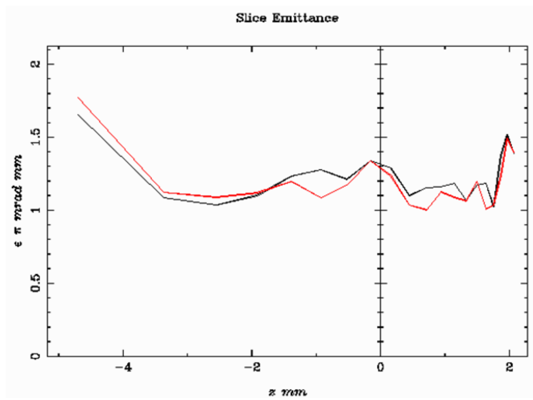
• At lower charges per bunch, MBI can be generally controlled and no beam heating is required anymore. Lower longitudinal emittances become now possible and available resulting in an increased 6D brightness and thus in a reduction of the FEL gain length. In this low charge regime, normalized longitudinal emittances in the µm range are desirable.

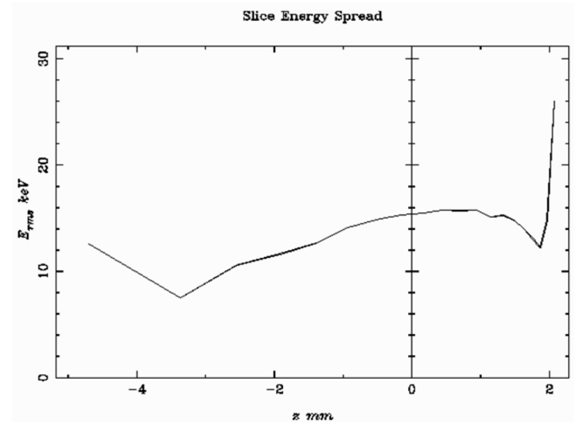
• For a clean and effective bunch compression, it is important that high order longitudinal phase-space correlation (beyond 2nd order) to be controlled.

"Slice" and "Projected" Quantities

• An important remark: in FELs, the **requirements** on beam parameters such as emittance, peak current and energy spread **need to be satisfied only in the longitudinal portion of the electron beam where lasing is desired.**







• The length of this region must be greater than the electron to photon slippage along the undulator, but it is ultimately defined by the FEL mode of operation, the experimental tolerances and the fluctuations of the relevant parameters.

• For example, in seeded FEL schemes, such a length must be longer than the seeding laser pulse convoluted with the total jitter between the electron and laser pulses. The term '**slice**' is usually associated with a beam quantity measured within this 'lasing' part of the beam (or to a fraction of it), while the term '**projected**' is referred to a property of the whole beam.

• On the contrary, **in ERLs are the projected characteristics** to be **important**

Energy

- **Most of the emittance increase due to space charge happens in the low energy part of the injector, the electron gun.**

- **Space charge effect intensity scales as γ^{-2} so higher energies at the gun are beneficial in minimizing such effects.**

- **Extensive simulation work and experimental evidence (Spring-8) showed that an energy of at least 500 keV is necessary to achieve the required beam quality within the charge/bunch range of interest.**

- **In a high brightness injector the final electron beam energy must be high enough to make residual space charge effects negligible. The actual value for such an energy depends on the bunch characteristics but it is typically found to be around 100 MeV or more.**

- Bazarov, I .V., and Sinclair, C .K., Phys. Rev. ST Accel. and Beams 8 034202 (2005).
- T. Shintake, et al., Phys. Rev. ST Accel. and Beams 12, 070701 (2009).

Accelerating Gradient at the Cathode

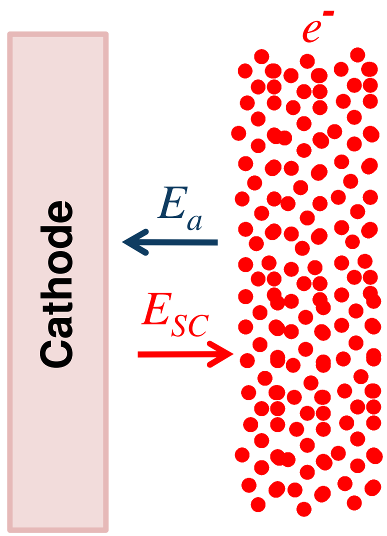
- **During emission at the cathode**, the electric field E_{SC} due to the already emitted electrons presents opposite direction with respect to E_a , the accelerating field in the gun.

  The **emission can continue** until E_{SC} **cancels** E_a.

  The **max charge density that can be emitted by a given** E_a is known as the '**space-charge limit**' and scales linearly with E_a.

  Higher gradients are required to **extract higher charge/bunch** and preserve beam quality.
  (1 nC bunch with $\varepsilon_{xn, yn} = 1\ \mu\text{m}$ requires $E_a > \sim 10\text{-}15$ MV/m)

  More on the space-charge limit later in the lecture.

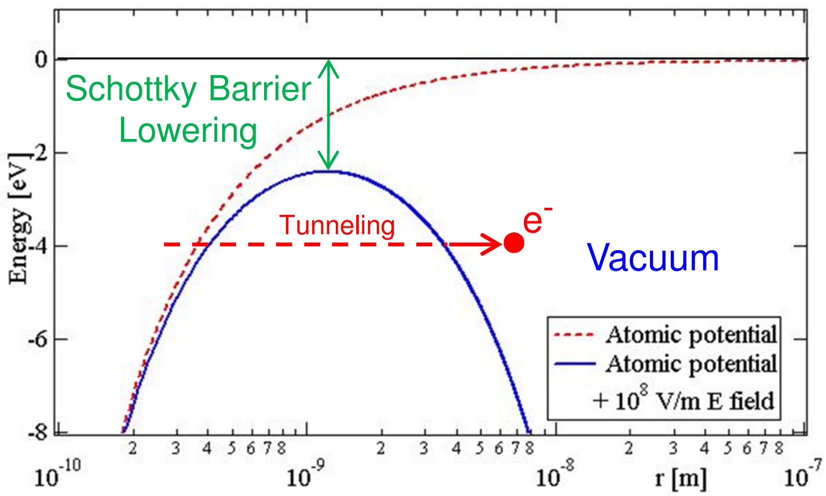


- Also, **larger gradients** allow for a '**faster' acceleration of the beam** towards higher energies **minimizing the deleterious effects of space charge** forces.

- There is a special mode of operation, the so-called '**beam blowout**' where a pancake like beam is emitted and evolves under the action of its own space charge forces.
  Such a mode of operation **requires relatively high gradients at the cathode**.
  More in following lectures.

Dark Current

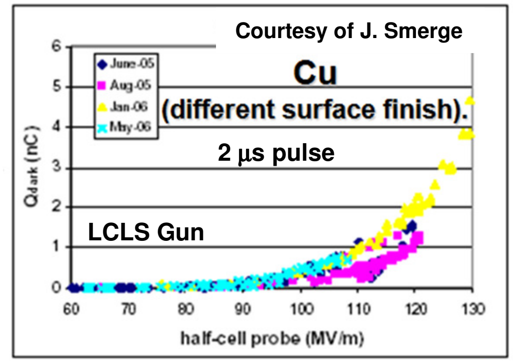
Dark current is mainly generated by field emission from the accelerator parts.



$$V_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} + e\left|\bar{E}\right| r$$

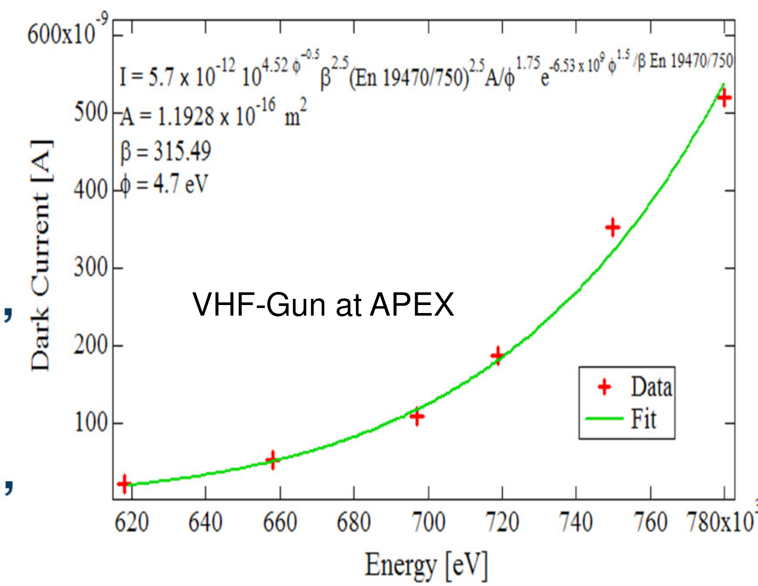
$$\left|\bar{E}\right| = \text{constant}$$

$$\left|\bar{E}\right| > \sim 10^8 \div 10^9\, V/m$$



- **Dark current can be tolerated in pulsed injectors but represents a serious issue in injectors running in high duty cycle mode where it can generate damage, quenching, and high radiation levels in the downstream accelerator.**

- **While no definitive 'cure' for dark current exists, all techniques for minimizing it should be used (surface finish and cleaning, geometry, materials, …). Also, high accelerating fields in the cathode area, which can increase field emission, should be carefully evaluated in terms of dark current.**

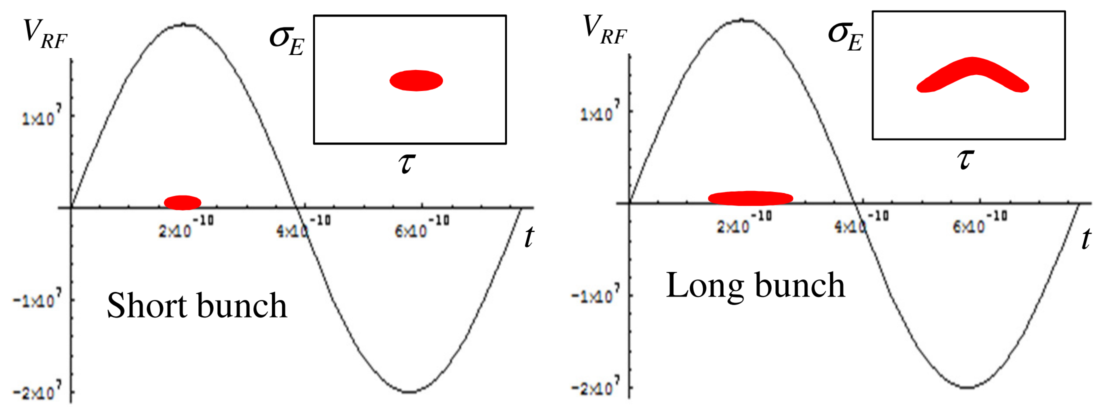


Bunch Length

- The bunch length is an important knob for controlling the charge density of the electron beam and hence space charge effects along the injector.

- In particular, longer bunches at the cathode can be used for mitigating space-charge induced emittance increase, especially when relatively low accelerating gradients at the electron gun are available.

- Other factors can limit the maximum bunch length.
For example, longer bunches sample more RF nonlinearities in the accelerating RF sections.
Also as we will see later, transverse emittance dilution due to RF scales with the square of the bunch length.



- The capability of controlling the longitudinal and transverse beam distributions is also important for the beam dynamics performance.
- For this requirement, photo-cathode systems represents an appealing choice because they allow controlling the electron beam distribution by shaping the pulse of the laser used for the photoemission (more on cathode systems later).

Peak Current

- **FEL gain depends on the bunch peak current.** For high-gain FEL schemes, values of up to few kA are typically required.

$$P(z) = P_0 e^{z/L_G} \qquad L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho_{Pierce}^{1D}} \quad gain\ \ length$$

$$\rho_{Pierce}^{1D} = \frac{1}{\gamma}\left[\frac{1}{64\pi^2}\frac{I_e}{I_A}\frac{1}{\varepsilon_x\beta_x}\lambda_u^2 K^2 JJ^2\right]^{1/3}$$

- **Oscillator FEL** schemes include storage cavities for the X-Ray pulses, and are usually operated in low-gain regime hence requiring smaller peak currents.

- Such high-peak currents are obtained by **compressing the bunch length along the accelerator in several stages.** Typical schemes include one or more **magnetic chicanes** in the linac, and in some cases **buncher systems** and/or **velocity bunching in the injector.**

- Typical **peak currents** required **at the injector exit**, compatible with reasonable compression factors in the downstream linac, depend on bunch charge and range in the several **tens of A.**

- More on compression later in next lectures.

Transverse Beam Size

Transverse emittance dilution due to RF scales with the square of the transverse rms size of the bunch.

(More in following lectures).

- **Aberrations in magnetic and electromagnetic components can strongly depends on beam sizes and can generate an increase of the transverse rms emittance.**

- **Larger beam sizes requires larger vacuum chamber cross-sections, larger bore magnetic components, making such components bigger and more expensive.**

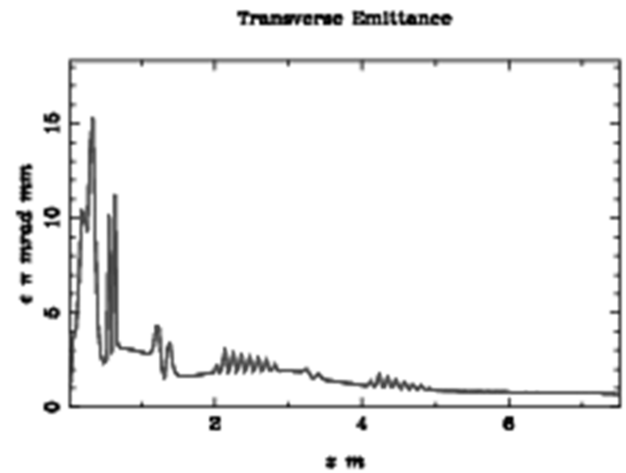
- **The rms beam size inside the typical high brightness gun ranges from few hundreds microns up to few mm.**

- **The average beam size along the injector decreases linearly with the beam energy due to the geometric emittance scaling with energy.**

Compatibility with Magnetic Field

• High-brightness injector schemes should be compatible with the application of magnetic fields in the cathode/gun area.

• Indeed, preserving the gun brightness along the injector requires techniques such as emittance compensation that requires magnetic fields in the gun region.
(More in the following lectures)

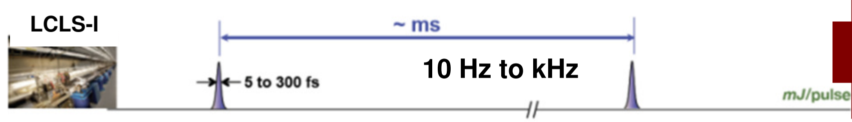


• Additionally, some of the proposed emittance exchange techniques requires the presence magnetic fields in the cathode region.
(More in later lectures).

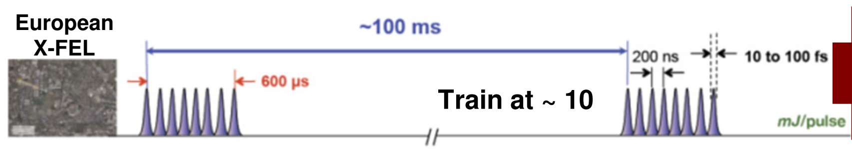
Repetition Rate

The repetition rate is a parameter that deeply impacts the technological choices for a 4th generation light source.

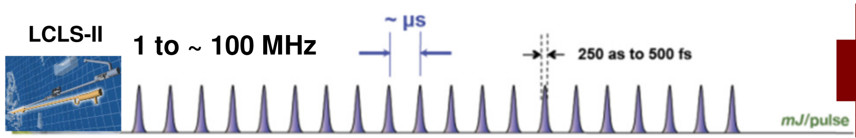
Indeed, it determines the injector and linac technologies and has a relevant impact on the facility cost, and also, as it will be discussed later, on the electron beam beam dynamics.



Normal-conducting linacs (S, C or X-Band); low repetition-rate gun.

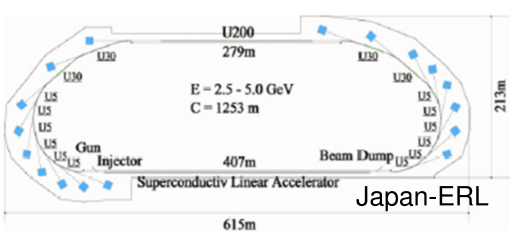


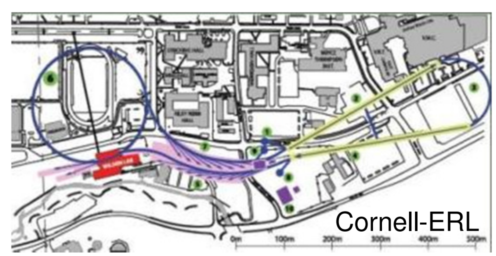
Normal or super-conducting linac; low repetition-rate gun.



Super-conducting linac; high repetition-rate gun.
(presently proposed XFEL oscillators requires ~ 1 MHz)

ERLs target 100s of mA average currents requiring GHz-class repetition rates





and hence super-conducting linac and high repetition-rate gun.

Technology Driven Low & High Gun Gradient Regimes

• To preserve brightness, it is desirable to accelerate the beam as quickly as possible, thus 'freezing-in' the space charge forces, before they can significantly dilute the phase space.

• In the case of high repetition rate injectors, as it will be discussed in Lecture LM2, technology limitations and/or or dark current mitigation, significantly reduces the peak accelerating gradients at the cathode with respect to those in pulsed low repetition rate systems.

• This situation can have a significant impact on beam dynamics.

• Space charge can be controlled by reducing the beam charge density, especially in the cathode region where the beam energy is low.

The use of larger transverse beam sizes at the cathode to reduce the density is carefully minimized because it increases the cathode thermal emittance.

• Instead, the bunch length is used, and longer bunches are required for lower gradients.

That increases the longitudinal emittance, but for most cases this is tolerable.

• As a consequence, in high repetition rate injectors, the bunch length at the cathode can be significantly longer than required at the FEL undulator entrance. This in turn necessitates relatively larger compression factors both at the injector and in the main linac.

Vacuum Performance

As it will be discussed later in the next lecture, the large majority of cathode systems used in high-brightness injectors are based on photo-cathodes.

In the low repetition-rate case, metal cathodes (mainly copper) have been extensively used because of their relatively simple preparation and robustness.

In the high repetition-rate case, metals cannot be used because of their low quantum efficiency QE in the 10^{-5} range (number of photo-emitted electrons per impinging photon), which would require unrealistic laser powers.

Higher QE materials, in the 10^{-2} range, are required in the high repetition-rate case.
Several materials have been already successfully developed and tested and many other promising candidates are under investigation.

Most of such materials are very reactive and/or their emitting surface is sensitive to damage by ion back-bombardment. Indeed, in order to achieve lifetimes compatible with the operation of a user facility, vacuum pressures ranging from 10^{-7} to 10^{-9} Pa (~10^{-9} to 10^{-11} Torr) are necessary (with even lower partial pressures for reactive residual gas molecules such as H_2O, O_2, CO_2).

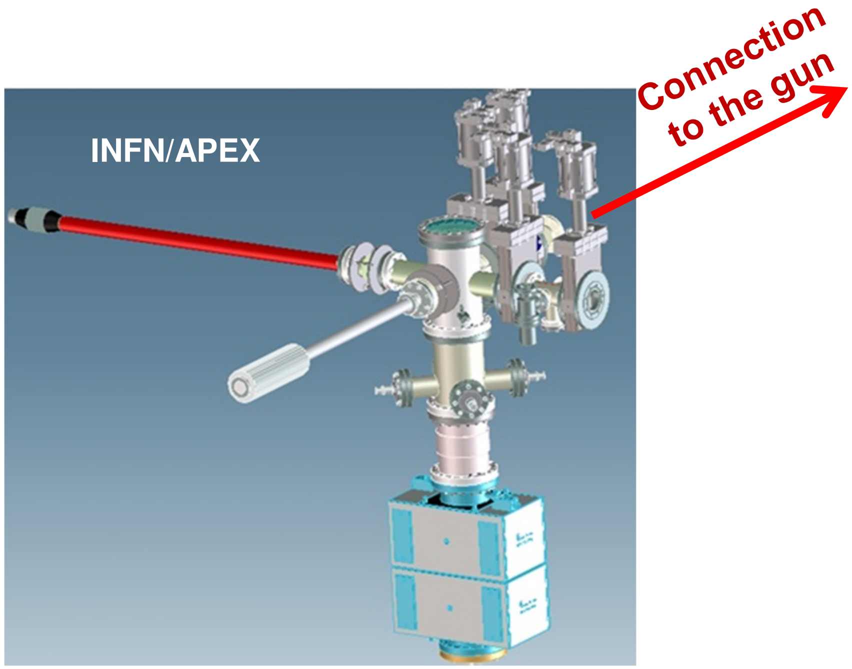
Reliability, Easiness of Operation

Independently from the gun/injector technology choice, the selected scheme should offer the required reliability and robustness to operate in an user facility and guarantee the proper continuity to the experimenters.

Also, replacement of parts with reduced lifetime should be performed as fast and efficiently as possible.

For example, in the case of delicate high-QE cathodes it is necessary to periodically replace and/or regenerate/activate the cathodes without breaking the vacuum pressure inside the gun.

To make that possible in a relatively straightforward and timely way, a vacuum load-lock system is usually required.



Injector Requirement Summary Table

Repetition rate	from ~ 10 Hz to ~ 1 MHz (FELs) up to ~ 1GHz and beyond (ERLs)	up to several 100s mA average current (ERLs)
Charge per bunch (depending on the operation mode)	from $\sim$ 1 pC to $\sim$ 1 nC	
Normalized transverse emittance (slice)	sub 10^{-7} m to 10^{-6} m (from low to high charge/bunch)	
Normalized longitudinal emittance	~ several μm at low charge outside the MBI regime	
Beam energy at the gun exit (to control space charge effects)	$\gtrsim$ 500 keV	
Beam energy at the injector exit	$\gtrsim$ 100 MeV	
Accelerating electric field at the cathode (to overcome the space charge limit)	$\gtrsim$ 10-15 MV/m	
Dark current	minimization is critical for high duty cycle injectors	
Bunch length at the cathode (to control space charge effects and for different modes of operation)	from $\sim$ 100 fs to tens of ps	
Peak current at the injector exit	tens of A in FEL's injectors	
Compatibility with magnetic fields in the cathode and gun regions (for emittance compensation and/or exchange techniques)		
Operational vacuum pressure at the electron gun (compatible with damage-sensitive cathodes)	10^{-7} - 10^{-9} Pa ($\sim 10^{-9}$ - $\sim 10^{-11}$ Torr)	
'Easy and fast' replacement of cathodes at the electron gun		
High reliability required to operate in an user facility		

F. Sannibale, D. Filippetto, C. F. Papadopoulos. Journal of Modern Optics **58**, 1419 (2011).

HOMEWORK

• Explain the relevance and importance of injectors in 4th generation light sources.

• Is there a parameter in electron sources that synthesizes the overall performance of the injector?
If that is the case define and discuss it.

• Describe the differences between the several definitions of emittance and their invariance conditions.

• Explain why the ultimate beam characteristics in a linac based facility are defined at the injector. In particular, identify the force that plays a major role in the injector. Describe the main effects of that force on the electron beam.